Collider Physics at NLO and the Monte Carlo MCFM

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Outline

- Introduction to Next-to-Leading-Order QCD
- Status of NLO: where we are now
- Why is NLO so difficult?
- Glimpses of the future: new directions for NLO calculations
- Introduction to MCFM
- MCFM at work: $W + 2$ jet production
- Summary

What is NLO?

In the context of this talk, I will use NLO to mean:

- $\mathcal{O}(\alpha_s)$ corrections to tree-level processes
  - graphs involving *one* virtual loop
  - no resummation of logarithms
  - no power corrections
  - no matching with parton showers
- When discussing NLO programs, they will not be event generators
  - predictions are parton level only, with no showering, hadronization or detector effects
  - for processes involving jets, one jet will contain at most two partons
- I will focus on high-energy colliders, in particular hadron colliders such as the Tevatron and the LHC

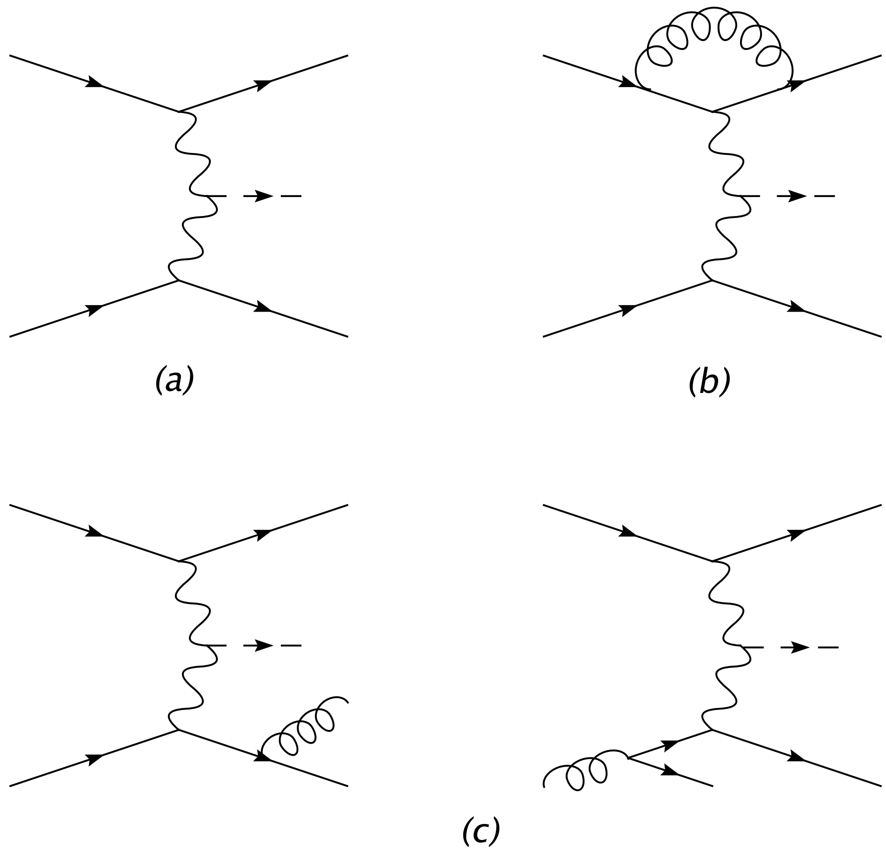
Why NLO?

The benefits of higher order calculations are well known

- Less sensitivity to unphysical input scales
  - first predictive normalization of observables at NLO
  - more accurate estimates of backgrounds for new physics searches and (hopefully) interpretation
  - confidence that cross-sections are under control for precision measurements
- More physics
  - jet merging
  - initial state radiation
  - more parton fluxes
- It represents the first step for a plethora of other techniques
  - matching with resummed calculations
  - NLO parton showers

NLO diagrams

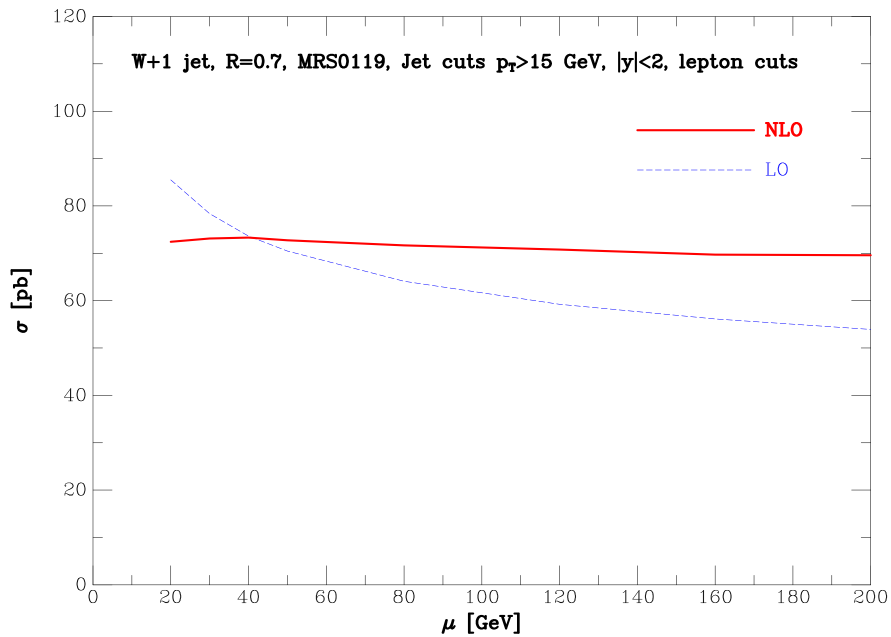
- Vector-boson fusion at a hadron-hadron collider: $pp \longrightarrow H + 2$ jets



- (a) Lowest order
- (b) NLO: virtual
- (c) NLO: real

Scale dependence

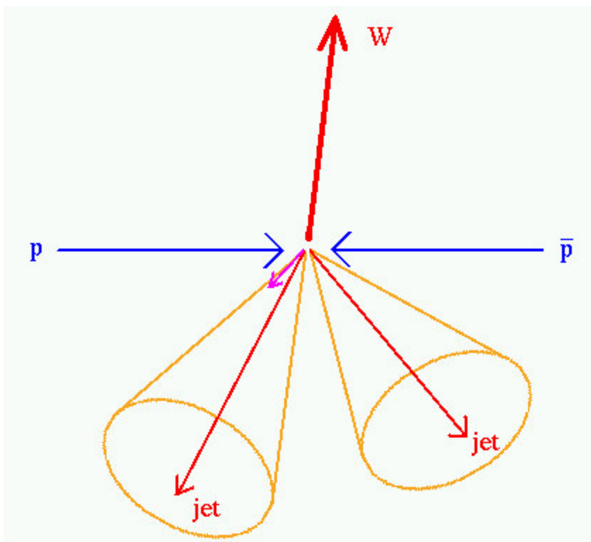
- $W + 1$ jet cross-section demonstrates the reduced scale dependence that is expected at NLO, as large logarithms are partially cancelled.

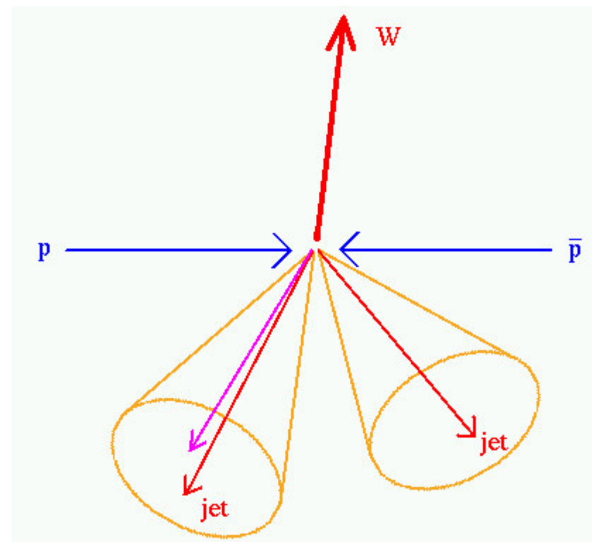


- Change between low ~ 20 GeV and high ~ 80 GeV scales is about 30% at LO and $< 5\%$ at NLO.

Next-to-leading order

- At next-to-leading order, we include an extra “unresolved” parton in the final state





- The theory begins to look more like an experimental jet, so one expects a better agreement with data.

So ....

If all this is true then, given that we have invested heavily (both financially and intellectually) in new upgrades and colliders like Run II of the Tevatron and the LHC:

- What's the current state-of-the-art?
  - NLO tools currently available
- Why are we lacking NLO predictions for many interesting (and crucial) processes?
  - traditional methods
  - difficulties and hurdles
- What's being done about it?
  - promising new directions

An experimenter's wishlist

- Hadron collider cross-sections one would like to know at NLO

Run II Monte Carlo Workshop, April 2001

Single boson	Diboson	Triboson	Heavy flavour
$W+\leq 5j$	$WW+\leq 5j$	$WWW+\leq 3j$	$t\bar{t}+\leq 3j$
$W+b\bar{b}+\leq 3j$	$WW+b\bar{b}+\leq 3j$	$WWW+b\bar{b}+\leq 3j$	$t\bar{t}+\gamma+\leq 2j$
$W+c\bar{c}+\leq 3j$	$WW+c\bar{c}+\leq 3j$	$WWW+\gamma\gamma+\leq 3j$	$t\bar{t}+W+\leq 2j$
$Z+\leq 5j$	$ZZ+\leq 5j$	$Z\gamma\gamma+\leq 3j$	$t\bar{t}+Z+\leq 2j$
$Z+b\bar{b}+\leq 3j$	$ZZ+b\bar{b}+\leq 3j$	$WZZ+\leq 3j$	$t\bar{t}+H+\leq 2j$
$Z+c\bar{c}+\leq 3j$	$ZZ+c\bar{c}+\leq 3j$	$ZZZ+\leq 3j$	$t\bar{b}+\leq 2j$
$\gamma+\leq 5j$	$\gamma\gamma+\leq 5j$		$b\bar{b}+\leq 3j$
$\gamma+b\bar{b}+\leq 3j$	$\gamma\gamma+b\bar{b}+\leq 3j$		
$\gamma+c\bar{c}+\leq 3j$	$\gamma\gamma+c\bar{c}+\leq 3j$		
	$WZ+\leq 5j$		
	$WZ+b\bar{b}+\leq 3j$		
	$WZ+c\bar{c}+\leq 3j$		
	$W\gamma+\leq 3j$		
	$Z\gamma+\leq 3j$		

NLOJET++

Author(s): Z. Nagy

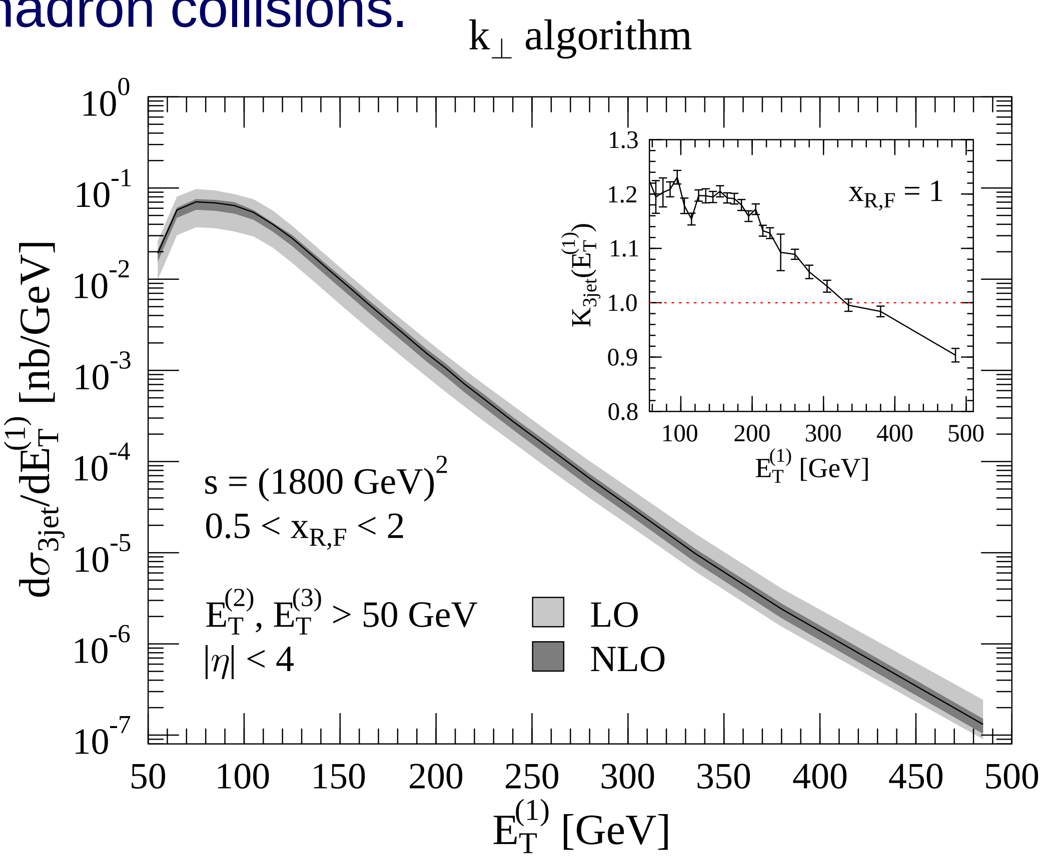
`http://www.ippp.dur.ac.uk/~nagyz/nlo++.html`

Multi-purpose C++ library for calculating jet cross-sections in e^+e^- annihilation, DIS and hadron-hadron collisions.

$e^+e^- \longrightarrow \ \leq 4$ jets

$ep \longrightarrow \ (\leq 3+1)$ jets

$p\bar{p} \longrightarrow \ \leq 3$ jets



hep-ph/0110315

AYLEN/EMILIA

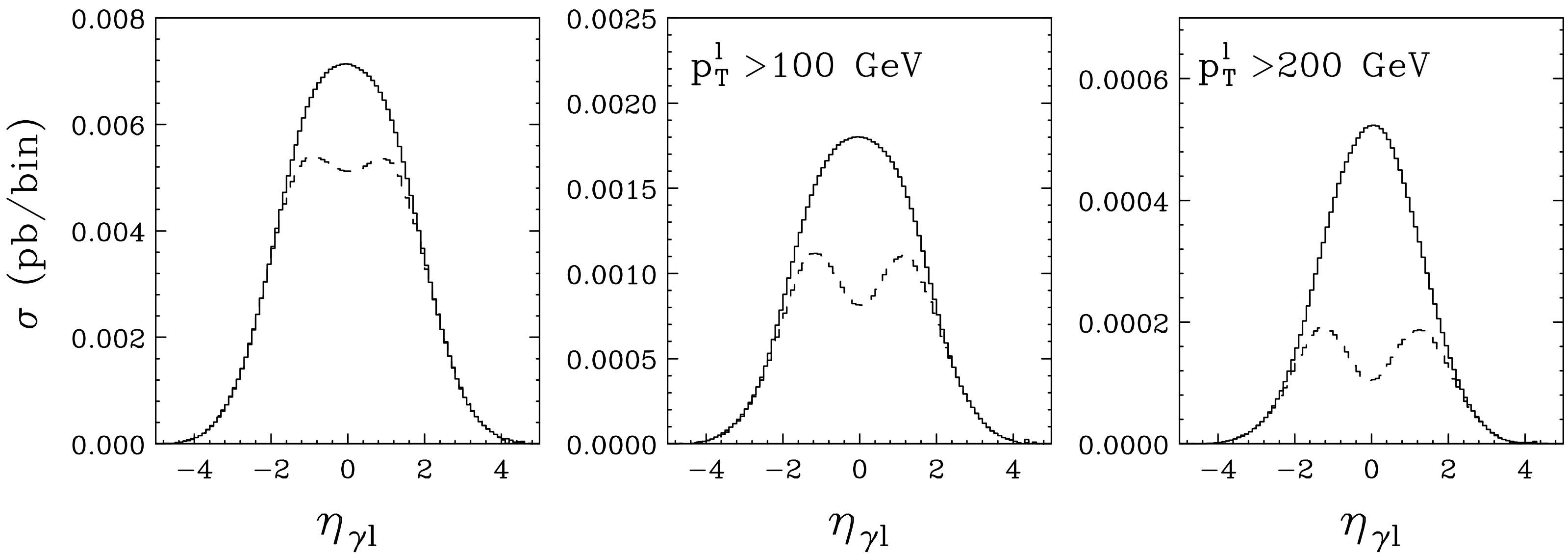
Author(s): L. Dixon, Z. Kunszt, A.Signer, D. de Florian

`http://www.itp.phys.ethz.ch/staff/dflorian/codes.html`

Fortran implementation of gauge boson pair production at hadron colliders, including full spin and decay angle correlations.

$p\bar{p} \longrightarrow VV'$ and $p\bar{p} \longrightarrow V\gamma$ with $V, V' = W, Z$

Anomalous triple gauge boson couplings at the LHC:



hep-ph/0002138

MCFM

Author(s): JC, R. K. Ellis

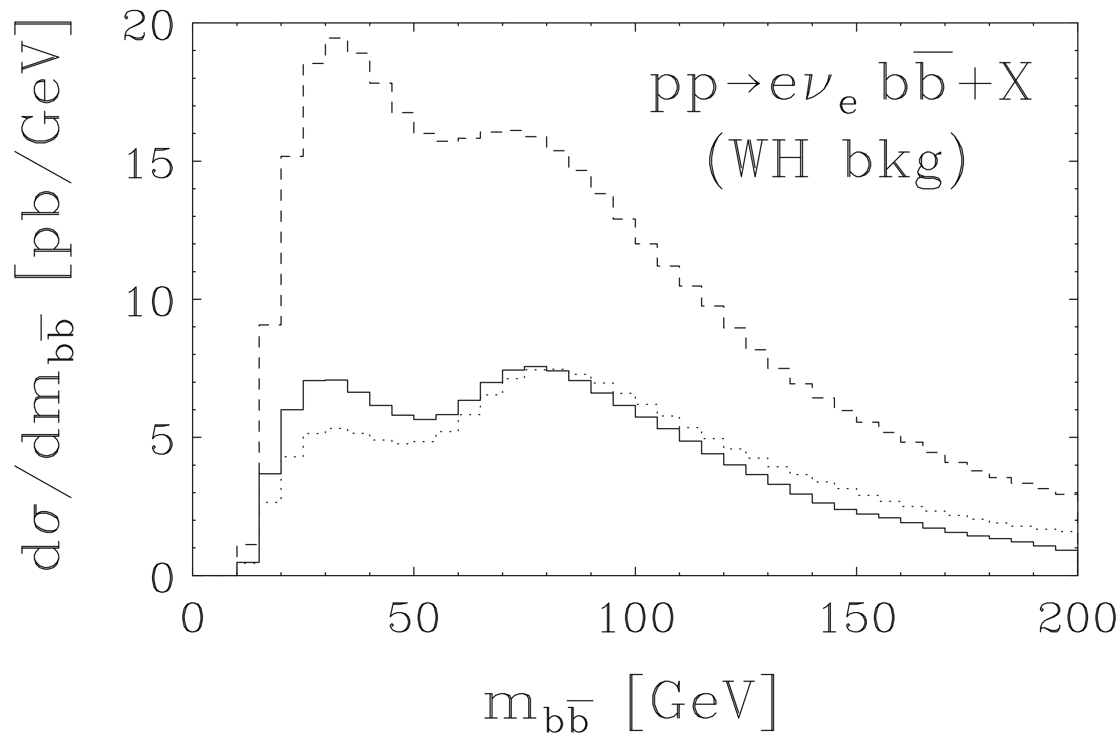
http://mcfm.fnal.gov

Fortran package for calculating a number of processes involving vector bosons, Higgs, jets and heavy quarks at hadron colliders.

$p\bar{p} \longrightarrow V + \leq 2$ jets

$p\bar{p} \longrightarrow V + b\bar{b}$

with $V = W, Z$.

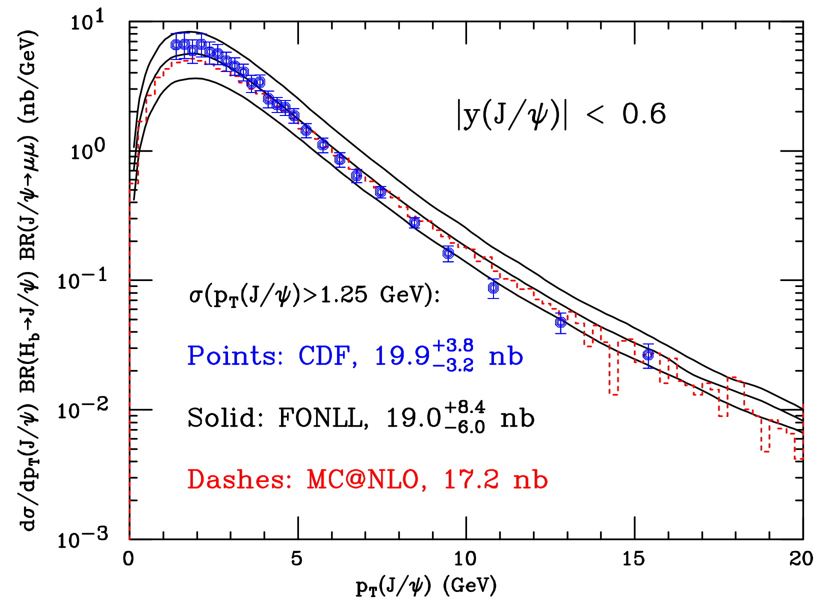


hep-ph/0308195

Heavy quark production

Author(s): M. L. Mangano, P. Nason and G. Ridolfi
`http://www.ge.infn.it/~ridolfi/hvqlibx.tgz`
Fortran code for the calculation of heavy quark cross-sections and distributions in a fully differential manner

- Based on the more inclusive calculations of Dawson et al, Beenakker et al.
- Does not include multiple gluon radiation, $\log(p_T/m_b)$ (FONLL)
  Cacciari et al., hep-ph/9803400
- These are the same matrix elements that are incorporated into MC@NLO
  Frixione et al., hep-ph/0305252



hep-ph/0312132

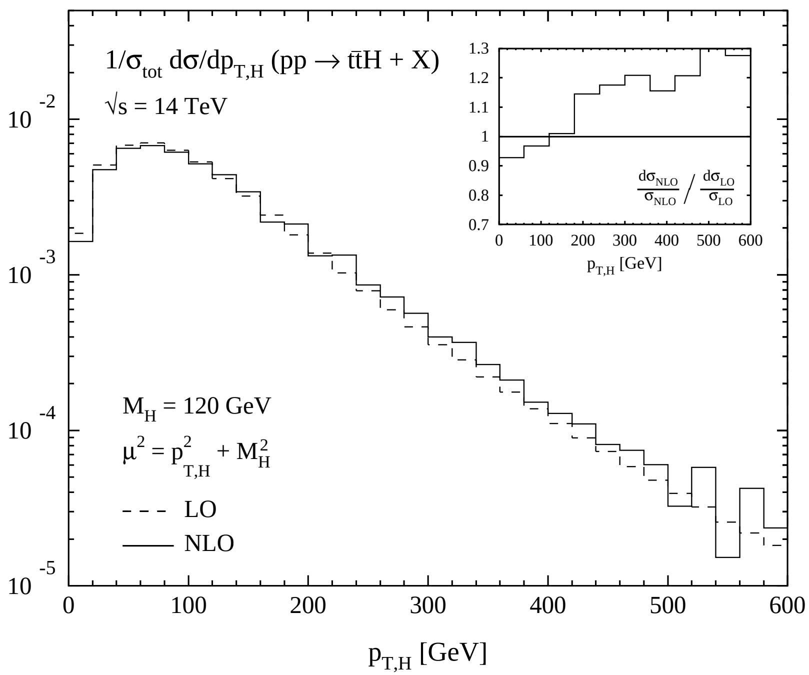
$Higgs + Q\bar{Q}$

Author(s): S. Dawson, C. B. Jackson, L. H. Orr, L. Reina, D. Wackeroth; W. Beenakker, S. Dittmaier, M. Kramer, B.Plumper, M. Spira, P. Zerwas

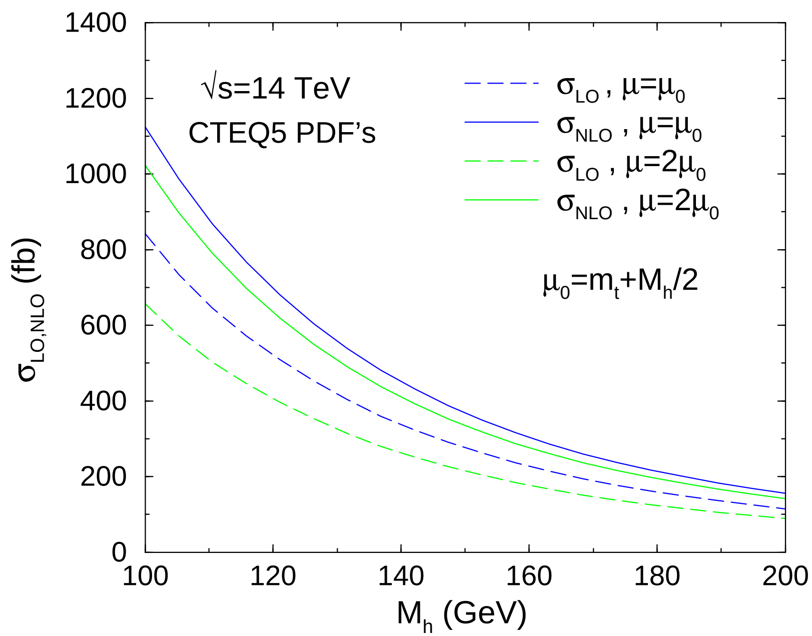
(No public code released)

Associated production of a Higgs and a pair of heavy quarks,

$$p\bar{p} \longrightarrow Q\bar{Q}H, \quad \text{with } Q = t, b.$$



hep-ph/0211352



hep-ph/0311216

Theoretical status

- Much smaller jet multiplicities, some categories untouched

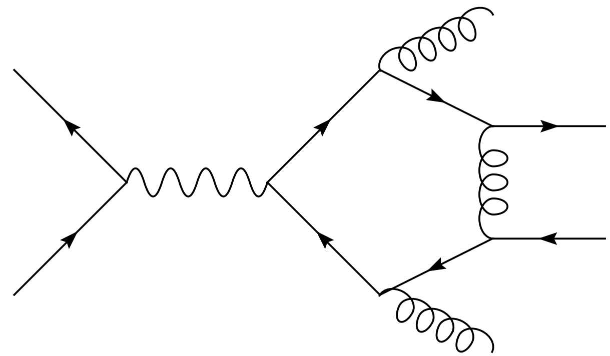
Single boson	Diboson	Triboson	Heavy flavour
$W + \leq 2j$	$WW + \leq 0j$	$WWW + \leq 3j$	$t\bar{t} + \leq 0j$
$W + b\bar{b} + \leq 0j$	$WW + b\bar{b} + \leq 3j$	$WWW + b\bar{b} + \leq 3j$	$t\bar{t} + \gamma + \leq 2j$
$W + c\bar{c} + \leq 0j$	$WW + c\bar{c} + \leq 3j$	$WWW + \gamma\gamma + \leq 3j$	$t\bar{t} + W + \leq 2j$
$Z + \leq 2j$	$ZZ + \leq 0j$	$Z\gamma\gamma + \leq 3j$	$t\bar{t} + Z + \leq 2j$
$Z + b\bar{b} + \leq 0j$	$ZZ + b\bar{b} + \leq 3j$	$WZZ + \leq 3j$	$t\bar{t} + H + \leq 0j$
$Z + c\bar{c} + \leq 0j$	$ZZ + c\bar{c} + \leq 3j$	$ZZZ + \leq 3j$	$t\bar{b} + \leq 0j$
$\gamma + \leq 1j$	$\gamma\gamma + \leq 1j$		$b\bar{b} + \leq 0j$
$\gamma + b\bar{b} + \leq 3j$	$\gamma\gamma + b\bar{b} + \leq 3j$		
$\gamma + c\bar{c} + \leq 3j$	$\gamma\gamma + c\bar{c} + \leq 3j$		
	$WZ + \leq 0j$		
	$WZ + b\bar{b} + \leq 3j$		
	$WZ + c\bar{c} + \leq 3j$		
	$W\gamma + \leq 0j$		
	$Z\gamma + \leq 0j$		

NLO basics

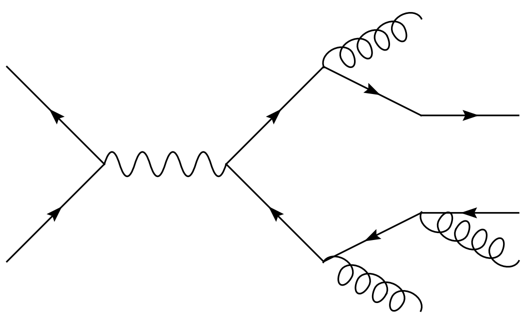
VIRTUAL

$$\int d^{4-2\epsilon}\ell \;\; 2\mathcal{M}^*_{loop}\,\mathcal{M}_{tree}$$

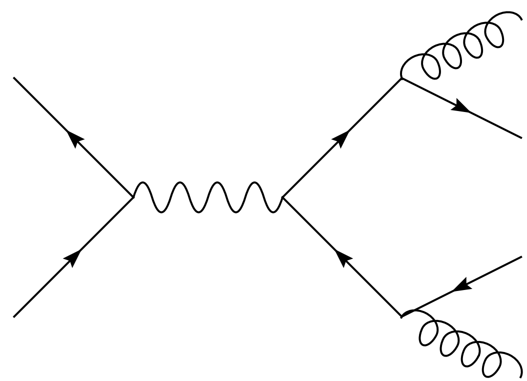
$$= \left(\tfrac{A}{\epsilon^2} + \tfrac{B}{\epsilon}\right)\, \left|\mathcal{M}_{tree}\right|^2$$



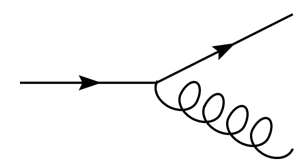
REAL



$$\longrightarrow$$



$$\otimes$$



$$\left|\mathcal{M}_{tree+1}\right|^2$$

$$\left|\mathcal{M}_{tree}\right|^2$$

$$\int (Split)\, dPS$$

$$= -\left(\tfrac{A}{\epsilon^2} + \tfrac{B}{\epsilon}\right)$$

Slow progress

- Why has progress been so slow?

$e^+e^- \longrightarrow 3$ jets c. 1980

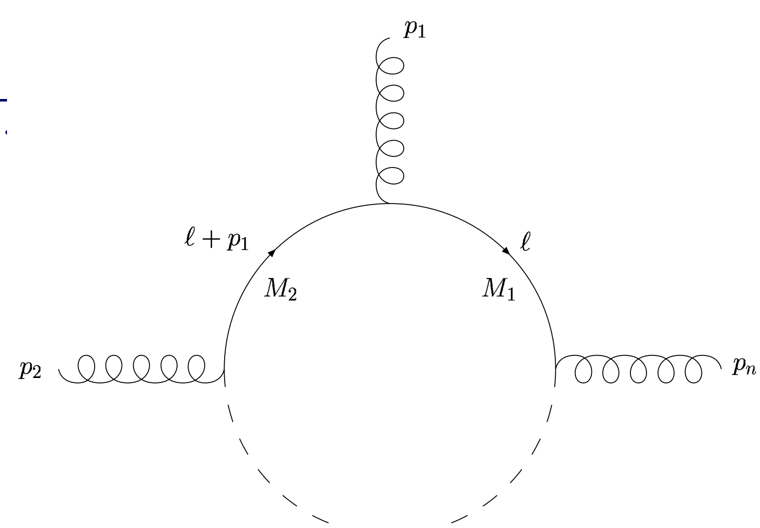
R. K. Ellis et al., 1981

$e^+e^- \longrightarrow 4$ jets c. 2000

Bern et al., Glover et al., 1996-7

- More particles $\rightarrow$ many scales $\rightarrow$ lengthy analytic expressions
- Integrals are complicated and process-specific:

$$\int d^{4-2\epsilon}\ell \, \frac{1}{(\ell^2-M_1^2)((\ell+p_1)^2-M_2^2)\ldots}$$



- different for:

$p_i^2 \neq 0$ W, Z, H

$M_i^2 \neq 0$ $t, b, \ldots$

Complications

- Fermions and non-Abelian couplings lead to more complicated tensor integrals:

$$\int d^{4-2\epsilon}\ell \, \frac{\ell^\mu}{(\ell^2 - M_1^2)((\ell + p_1)^2 - M_2^2)\ldots}$$

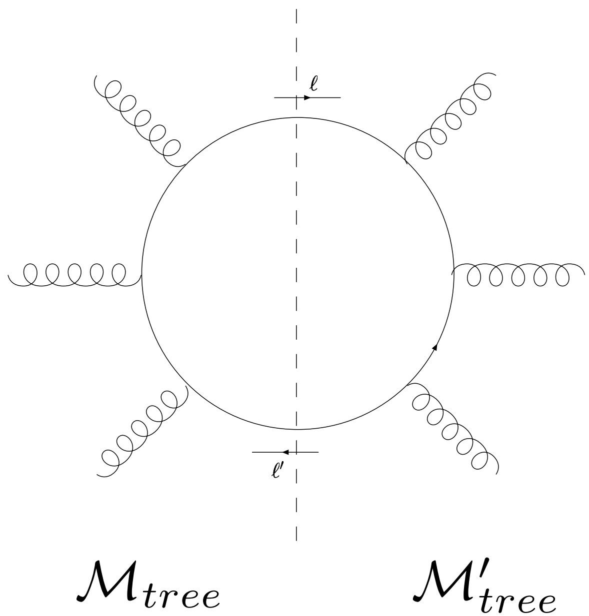
- Passarino-Veltman reduction in terms of scalar integrals:

$$\longrightarrow c_1 p_1^\mu + \ldots c_{n-1} p_{n-1}^\mu$$

  where the c_i are given by the solutions of $(n-1)$ equations

- This gives rise to the $(n-1) \times (n-1)$ Gram determinant, $\Delta = \det(2p_i \cdot p_j)$.
  - large intermediate expressions
  - spurious singularities

Unitarity technique



$$= \int dPS(\ell, \ell')\, \mathcal{M}_{tree} \times \mathcal{M}'_{tree}$$

- Standard tree-level tricks can be used to simplify amplitudes, yielding compact results

  e.g. Dixon, hep-ph/9601359

- Rational functions of invariants cannot be obtained easily with this method
- Not easy to generalize and automate, simplification by hand

Hexagons and beyond

- There is little computational experience with N-point intgerals beyond pentagons, $N = 5$: the NLO frontier is at $2 \rightarrow 3$ processes
- However, we know that all integrals with $N > 4$ can be written as a sum of known box integrals

Binoth et al., hep-ph/9911342

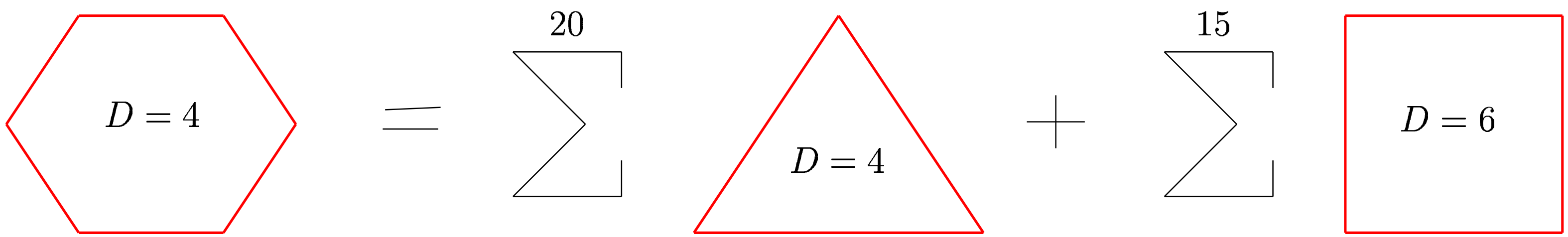
- Analytic result is:

$$N - \text{point finite part} = \sum^{m} \text{dilogarithms} + \text{simpler functions}$$

- For a hexagon integral with masses, $m > 1000$. This may lead to large cancellations in some kinematic regions and thus numerical instabilities
- Perhaps a numerical method could be just as good, or better

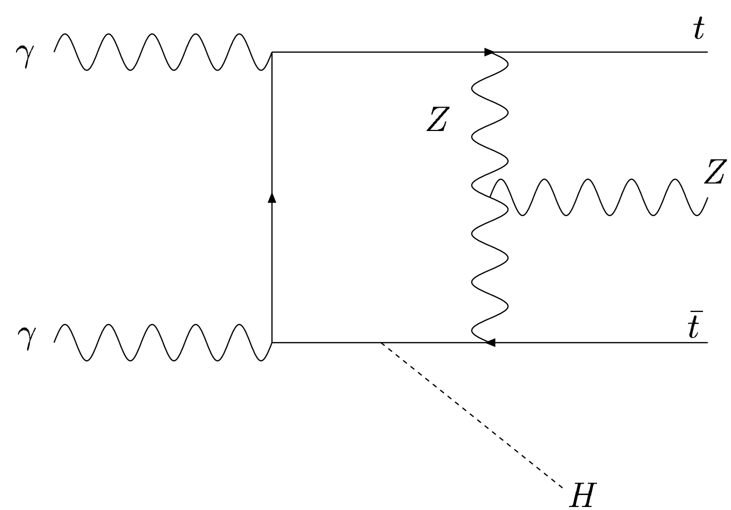
Binoth et al., hep-ph/0210023
Ferroglia et al., hep-ph/0209219

Numerical recipe



Hexagon reduction in terms of triangles and boxes

- A sector decomposition is used to simplify the integrals
- triangles $\longrightarrow$ 1-dim. integral
- boxes $\longrightarrow$ 2-dim. integral
- Integration by a combination of standard techniques and Monte Carlo



IR-divergent loop integrals

- The IR singularities can be isolated from the loop integrals using a simple technique

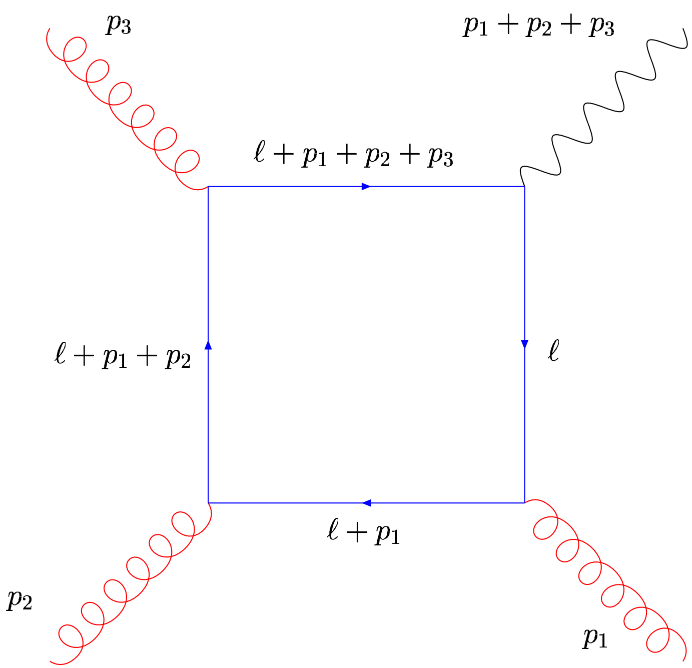
Dittmaier, hep-ph/0308246

- Singularities occur when:

a massless external particle splits into two massless internal lines	COLLINEAR
two external on-shell particles exchange a massless particle	SOFT

- These result in $\frac{1}{\epsilon}$, $\frac{1}{\epsilon^2}$ poles
- By identifying all the soft and collinear configurations in an integral, one can extract all the IR poles and obtain a finite integral that can be evaluated in 4 dimensions.
- Singular pieces are given in terms of related triangle integrals

Example



$p_1^2 = p_2^2 = p_3^2 = 0$

$\ell = -p_1 - p_2$
yields soft singularities

$\ell = xp_1$ for any arbitrary x
leads to collinear singularities

$$\frac{1}{(\ell+p_1+p_2)^2(\ell+p_1+p_2+p_3)^2} \longrightarrow$$
$$\frac{A}{(\ell+p_1+p_2)^2} + \frac{B}{(\ell+p_1+p_2+p_3)^2}$$

- This method has already been applied to pentagon integrals involved in the calculation of $t\bar{t}H$ production at NLO

Numerical approach

- If all singularities can be subtracted, perhaps loop integrals can be done numerically
- This method has many advantages:
  - a general solution for many processes, regardless of internal and external masses
  - extension to large final-state multiplicites limited only by CPU power
  - presence of masses in general should simplify the procedure (less singularities) rather than requiring much more work (cf. analytical approach)
- Problem: loop integrals also contain UV divergences

$$\int d^{4-2\epsilon}\ell \frac{\ell^\mu \ell^\nu}{\ell^2(\ell+p_1)^2(\ell+p_1+p_2)^2}$$

UV singularities

- Problem of UV subtraction solved and outlined by Nagy and Soper
  Nagy and Soper, hep-ph/0308127
- At the moment, limited to QCD with $m_Q = 0$
- Schematically,

$$\sum \underbrace{(\mathrm{Graph} - \mathrm{CT})}_{\text{finite}} + \underbrace{\left(\sum \mathrm{CT}\right)}_{\text{simple}}$$

  where CT stands for the sum of UV, soft and collinear counter-terms
- Loop integration can then be performed numerically
- General algorithm laid out, but the details of the numerical integration provide a topic for further study
  see also e.g. Soper, hep-ph/9804454
- Recent alternative proposed, isolating all IR and UV singularities
  Giele and Glover, hep-ph/0402152

Real contribution

- Relatively simple - diagrams and phase space can already be generated efficiently by tree level programs
- Methods for dealing with singular regions are well-developed, such as phase-space slicing and dipole subtraction
- However, for high multiplicity final states, the number of singular regions is large, resulting in:
  - Very many dipoles
  - Time-consuming calculation of subtraction terms
- Modifications to the original formalism have been made that limit the subtraction region and thus speed up the code

  Z. Nagy, hep-ph/0307268
- There's room for investigation of this implementation and further ideas

A different approach

- Try to construct infrared finite amplitudes for gauge theories with massless fermions

Forde and Signer, hep-ph/0311059

- Finite amplitudes would have many benefits:
  - Simple numerical approach
  - Easy matching to a parton shower

S-matrix elements in normal Fock space	$\longleftarrow$	soft and collinear divergences
$\Downarrow$		
order-by-order dressed states including all long-range interactions	$\longleftarrow$	free of infrared divergences

Basic idea

- Basic assumption when constructing amplitudes normally:

$$\underbrace{e^{-\imath tH}}_{\text{full Hamiltonian}} \quad \underbrace{|\Psi(t)\rangle}_{\text{exact state}} \longrightarrow \underbrace{e^{-\imath tH_0}}_{\text{free Hamiltonian}} \quad \underbrace{|\Phi(t)\rangle}_{\text{free state}} \quad \text{as } t \to \pm\infty$$

- This assumption is not true for QCD: massless gauge bosons have long-range interactions that do not vanish sufficiently quickly $\longrightarrow$ IR singularities
- Introduce an asymptotic Hamiltonian that contains the long-range interactions that give rise to soft and collinear splittings:

$$e^{-\imath tH_A}\,|\Omega(t)\rangle$$

- Diagrammatic rules similar to Feynman rules, but time-ordered
- So far, only demonstrated on a test case ($e^+e^- \to 2$ jets): no hadronic initial state, no triple-gluon coupling

NLO Summary

- NLO tools are an invaluable aid to experimental studies now and will continue to be so in the future
- There are many programs currently available for predictions at both existing and proposed colliders
  - author-controlled
    single top, $H + Q\bar{Q}$
  - single class of processes
    $V\gamma$, $Q\bar{Q}$
  - generic programs
    NLOJET++, PHOX-family, MCFM
- Despite recent progress towards NNLO predictions, there's still much left to be done at the one-loop level

NLO at Present

- Although there are now new methods being proposed for performing NLO (and beyond) calculations, the ideas are so far embryonic
- No method has yet been implemented in a practical form. Although the promise is great, for producing NLO predictions involving multi-particle final states, these methods still struggle to reproduce known results of 20 years ago
- Emerging data from the Tevatron Run II and studies for the LHC require NLO results now
- Thus there is still much effort devoted towards traditional calculations. One such implementation is the general purpose Monte Carlo MCFM

JC and R. K. Ellis

MCFM Summary - v. 3.4

$p\bar{p} \to W^\pm/Z$	$p\bar{p} \to W^+ + W^-$
$p\bar{p} \to W^\pm + Z$	$p\bar{p} \to Z + Z$
$p\bar{p} \to W^\pm + \gamma$	$p\bar{p} \to W^\pm/Z + H$
$p\bar{p} \to W^\pm + g^\star\,(\to b\bar{b})$	$p\bar{p} \to Zb\bar{b}$
$p\bar{p} \to W^\pm/Z +$ 1 jet	$p\bar{p} \to W^\pm/Z +$ 2 jets
$p\bar{p}(gg) \to H$	$p\bar{p}(gg) \to H +$ 1 jet
$p\bar{p}(VV) \to H +$ 2 jets	

- MCFM aims to provide a unified description of a number of hadron-hadron processes at NLO accuracy. More processes are available at LO only.
- Various leptonic and/or hadronic decays of vector bosons are included as further sub-processes.
- MCFM version 3.4.5 is part of the CDF code repository.

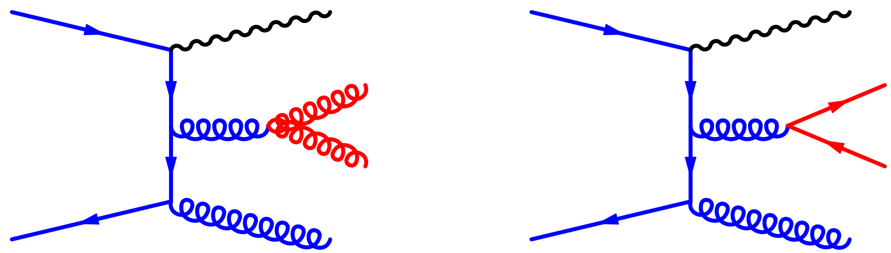
MCFM Information

- Version 3.4 available at:
  `http://mcfm.fnal.gov`
- Improvements over previous releases:
  - more processes
  - better user interface
  - support for PDFLIB, Les Houches PDF accord
    ($\longrightarrow$ PDF uncertainties)
  - ntuples as well as histograms
  - unweighted events
  - Pythia/Les Houches generator interface (LO)
  - ‘Behind-the-scenes’ efficiency
- Coming attractions:
  - even more processes
  - photon fragmentation

Example: $W+2$ *jet production at NLO*

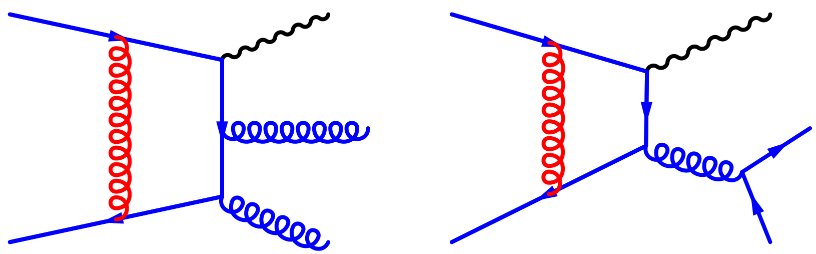
- Feynman diagrams for extra parton radiation, e.g.

soft gluon



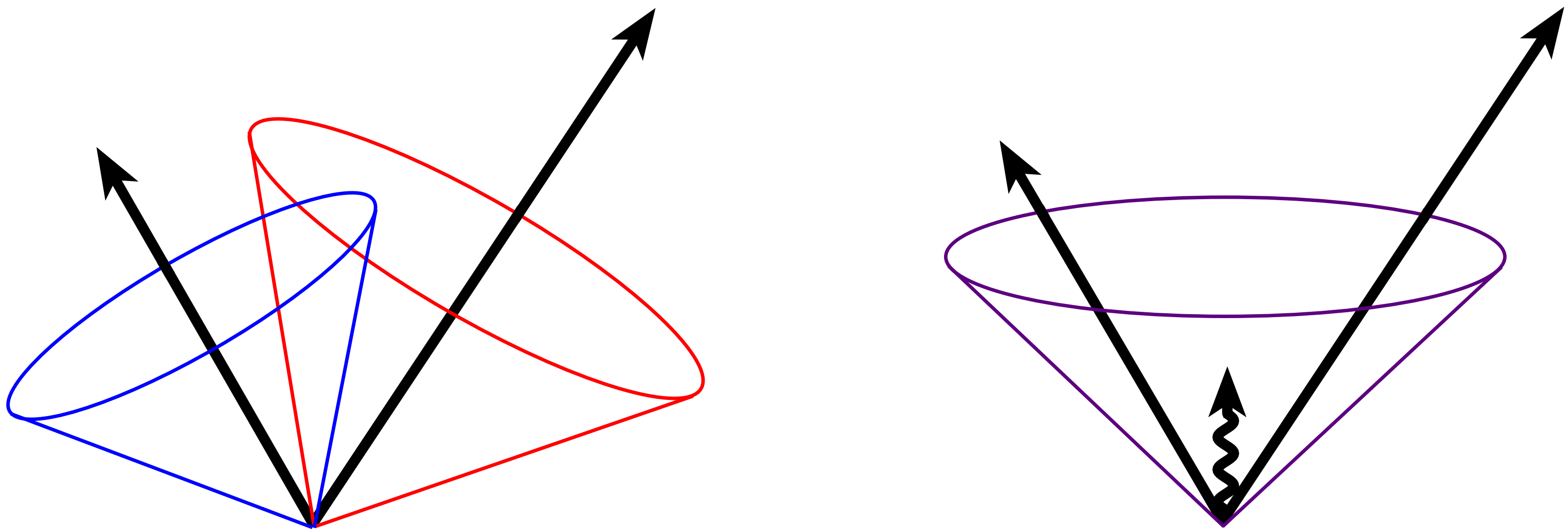
collinear quarks

- Loop diagrams, also one extra factor of α_S:



Defining a jet - cone algorithm

- Cone-based algorithm, $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} > R$.
- Very popular in Run I.
- Suffers from sensitivity to soft radiation at NLO.



- Instability can be mitigated by extra jet seeds, e.g. midpoint algorithms.

Defining a jet - k_T algorithm

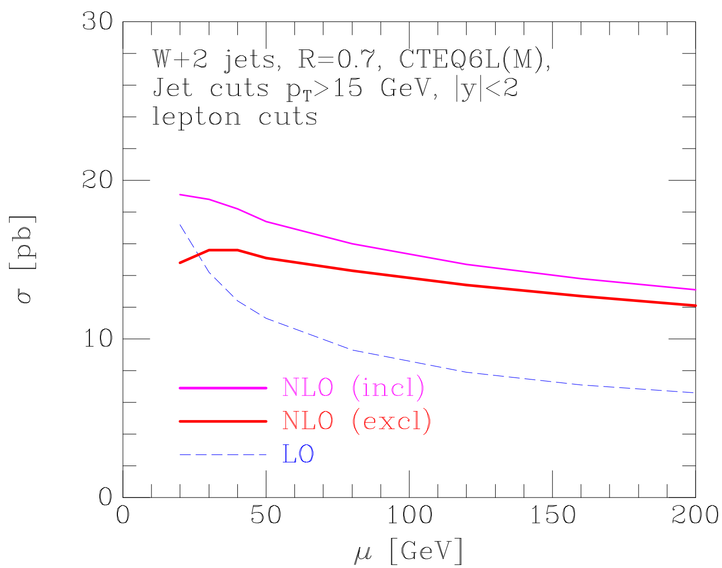
- Preferred by theory - insensitive to soft radiation, immediate matching to resummed calculations.
- Limited experimental use at hadron colliders due to difficulties with energy subtraction.
- Jets are clustered according to the relative transverse momentum of one jet with respect to another.
- Similarity with cone jets is kept, since the algorithm still terminates with all jets having $\Delta R > R$.
- We shall adopt the k_T prescription that is laid out for Run II (G. Blazey et al.), where other ambiguities such as the jet recombination scheme are fixed.

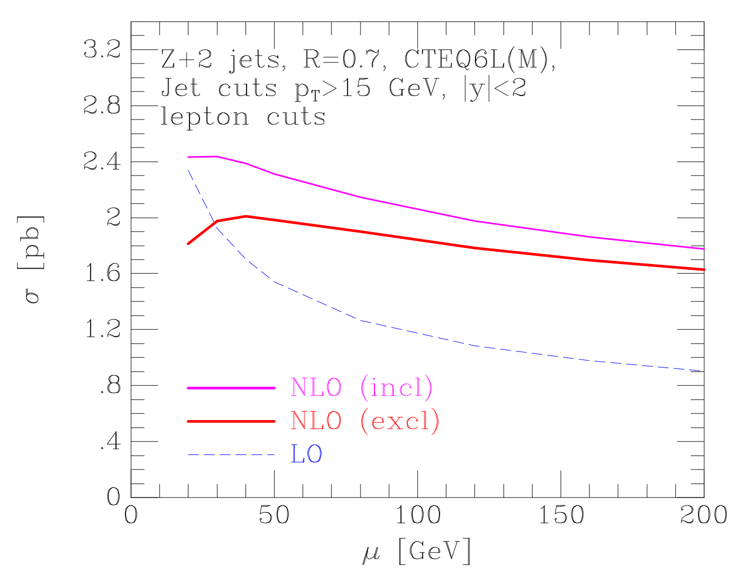
Tevatron event cuts

- k_T clustering algorithm with pseudo-cone size, $R = 0.7$.
- Jet cuts:
  $p_T^{\rm jet} > 15$ GeV, $|y^{\rm jet}| < 2$.
- Lepton cuts:
  $p_T^{\rm lepton} > 20$ GeV, $|y^{\rm lepton}| < 1$.
- (W only) Missing transverse momentum:
  $p_T^{\rm miss} > 20$ GeV.
- (Z only) Dilepton mass:
  $m_{e^-e^+} > 15$ GeV (since γ^* is also included).

Scale dependence

- Choose equal factorization and renormalization scales and examine the scale dependence of the $W, Z + 2$ jets cross-section at the Tevatron, in LO and NLO.

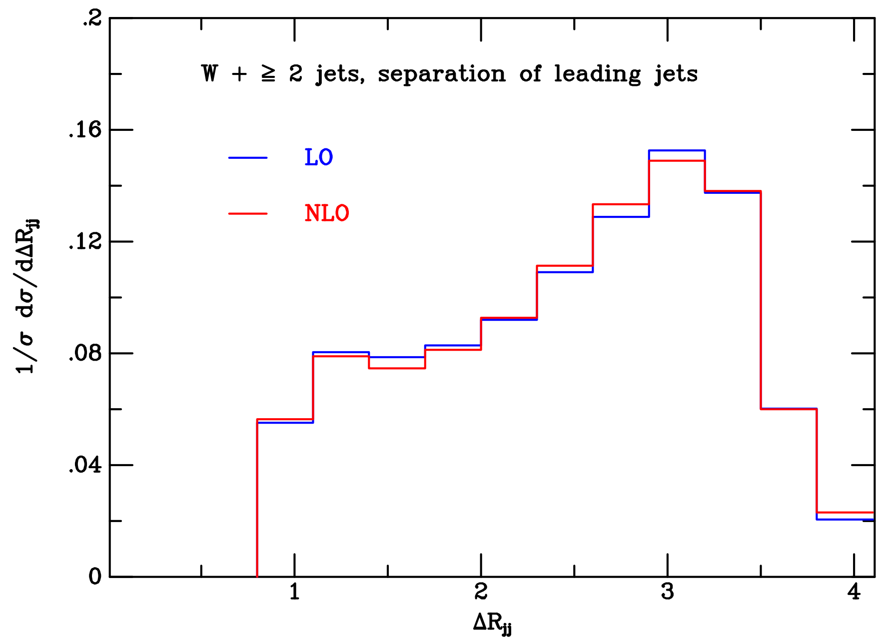




- Exclusive cross-section requires exactly 2 jets at NLO. Inclusive also includes the (lowest order) 3 jet contribution.
- Scale dependence is much reduced in both cases.

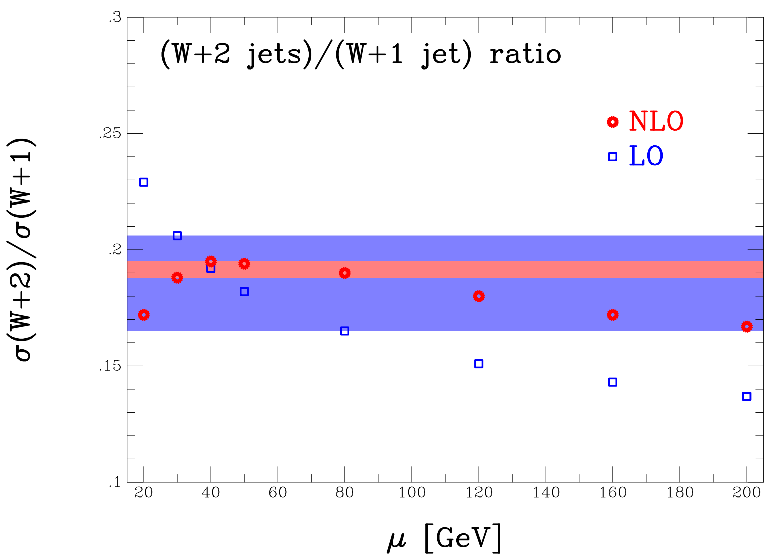
Jet-jet separation

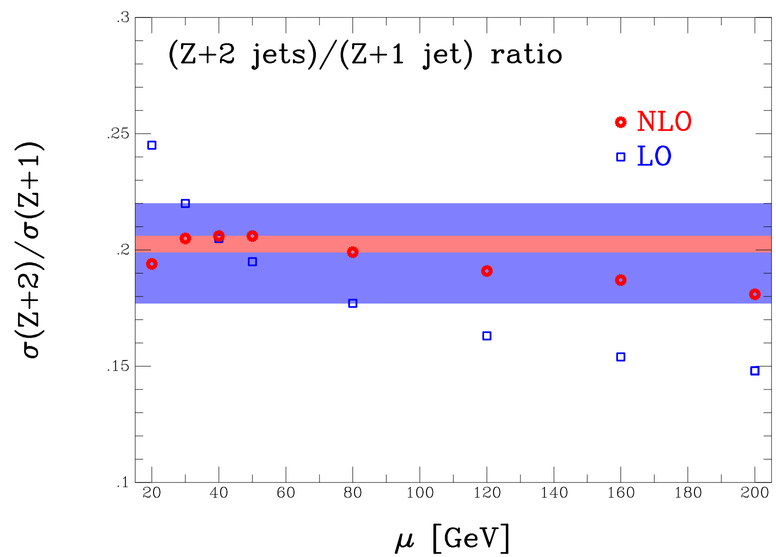
- In Run I, there was some discrepancy in the shape of the jet-jet separation ΔR_{jj} compared with LO theory.
- Results at NLO appear to confirm the leading order shape, with no significant dependence on scale.



Cross-section ratios at NLO

- Prediction for the (W+2 jet)/(W+1 jet) ratio in Run II. Preferred experimentally since some systematics cancel.





- As expected, much more stable at NLO than LO, particularly in the region of conventional scales $\sim 30 - 80$ GeV.
- More studies underway.

Heavy flavour content

- Many signals of new physics involve the production of a W or Z boson in association with a heavy particle that predominantly decays into a $b\bar{b}$ pair.
- Most well-known example is a light Higgs:

$$p\bar{p} \longrightarrow W(\rightarrow e\nu)H(\rightarrow b\bar{b})$$

$$p\bar{p} \longrightarrow Z(\rightarrow \nu\bar{\nu}, \ell\bar{\ell})H(\rightarrow b\bar{b})$$

- However, we will need to understand our SM backgrounds very well to perform this – or any similar – search.
- The largest background is ‘direct’ production:

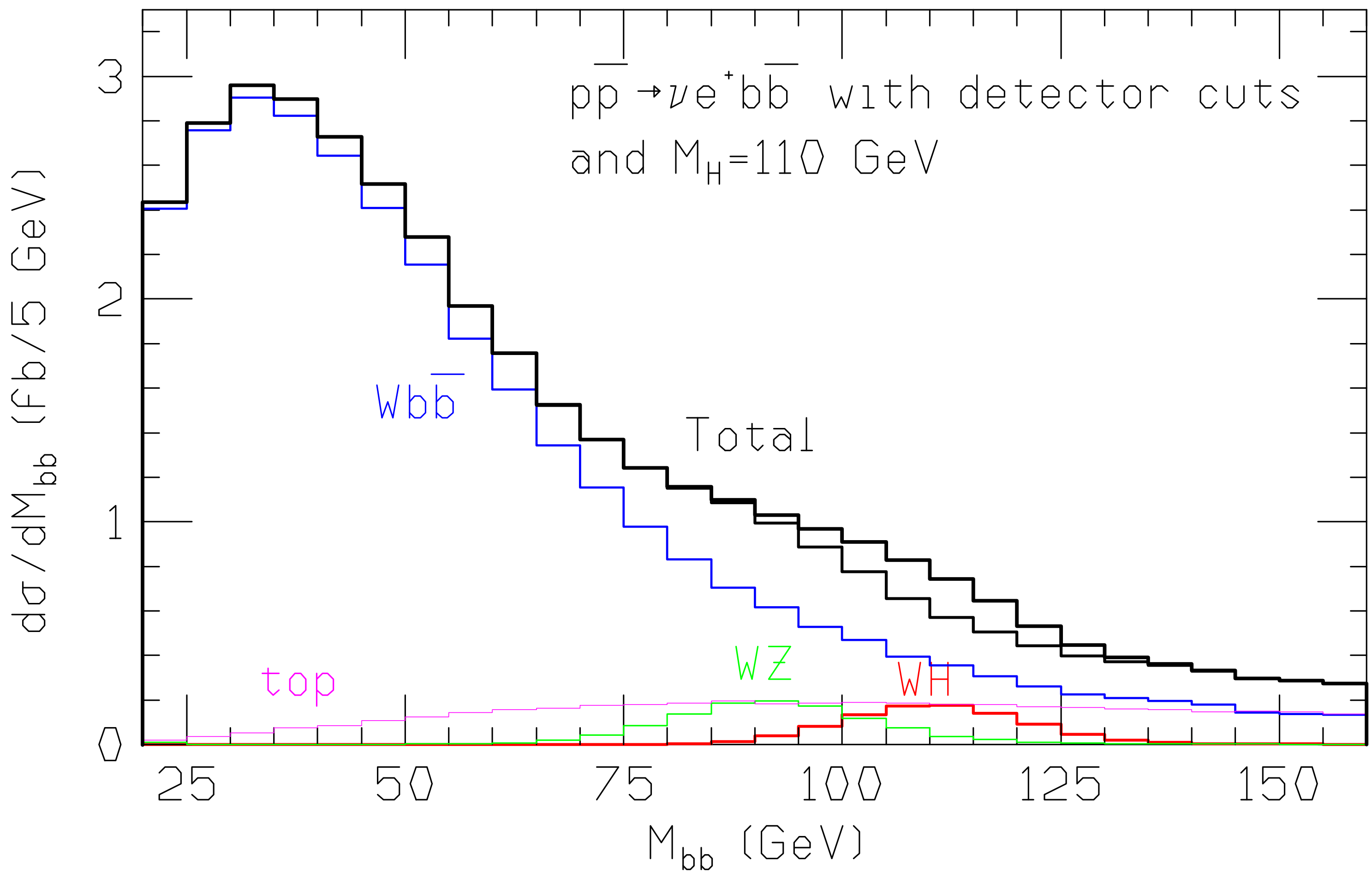
$$p\bar{p} \longrightarrow W\, g^{\star}(\rightarrow b\bar{b})$$

$$p\bar{p} \longrightarrow Z\, b\bar{b}$$

- Also important to understand these as backgrounds to signals that we expect, such as top.

Background importance

- NLO study of WH search using MCFM.



Predicting the $W b\bar{b}$ background

- There are a number of methods for predicting the Standard Model 'direct' background.
- Amongst the theoretical choices are:
  - Fixed order vs. event generator;
  - LO vs. NLO;
  - Pythia vs. Herwig;
  - Massive b's vs. Massless b's.
- Citing a 40% uncertainty on the leading-order calculation (M. Mangano), a recent study by CDF uses a mixed approach relying heavily on generic $W+$ jet data, but with some theoretical input.

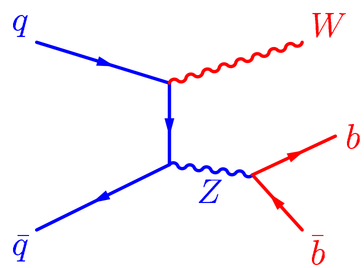
Hybrid recipe (CDF's 'Method 2')

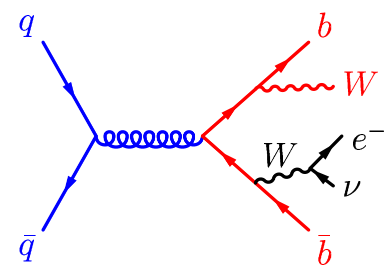
1. Measure the number of $W+2$ jet events.
2. Subtract the number of events predicted by theory from non-direct channels.
   - $t\bar{t}$ (Pythia norm. to NLO)
   - Diboson (Pythia norm. to NLO)
   - Single top (Pythia/Herwig norm. to NLO)
3. This estimates the number of direct $W+2$ jet events.
4. Use VECBOS (ALPGEN in Run II) (leading order) + Herwig to estimate the fraction of $W+2$ jet events that contain two b's.
5. Obtain prediction for direct $W+b\bar{b}$ events:

$$\sigma(Wb\bar{b}) = \left[\frac{\sigma(Wb\bar{b})}{\sigma(W+2\text{ jet})}\right]_{MC} \times \left[\sigma(W+2\text{ jet})\right]_{\text{data}}$$

Other $Wb\bar{b}$ backgrounds

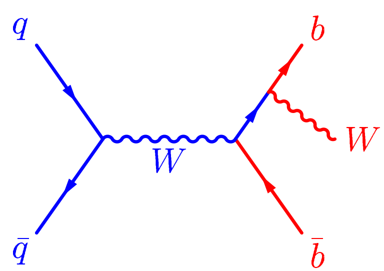
diboson

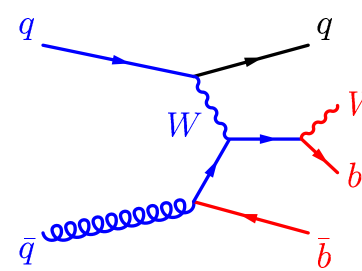




$t\bar{t}$

single
top (s)



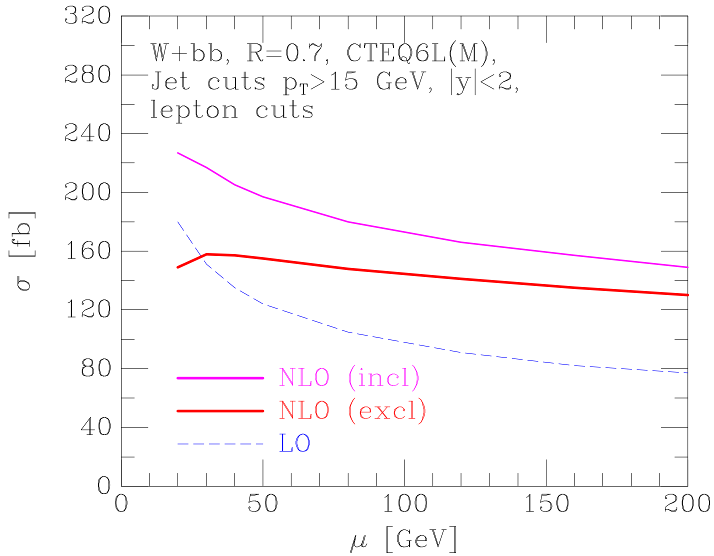


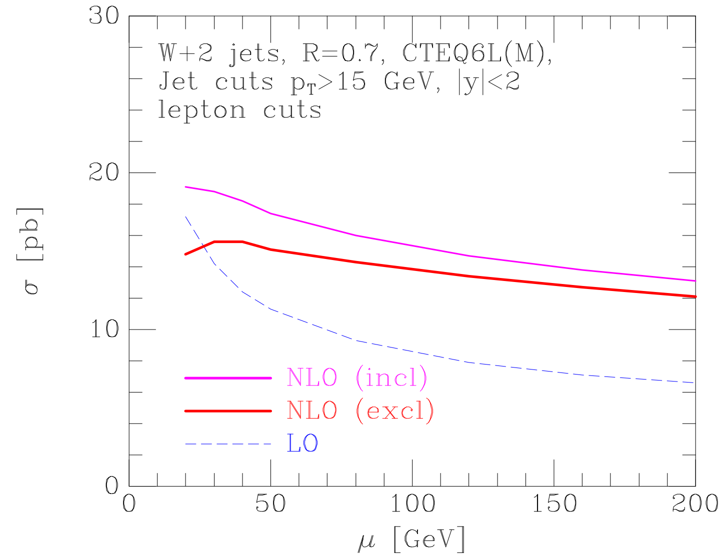
single
top (t)

Alternatives - is this the best we can do?

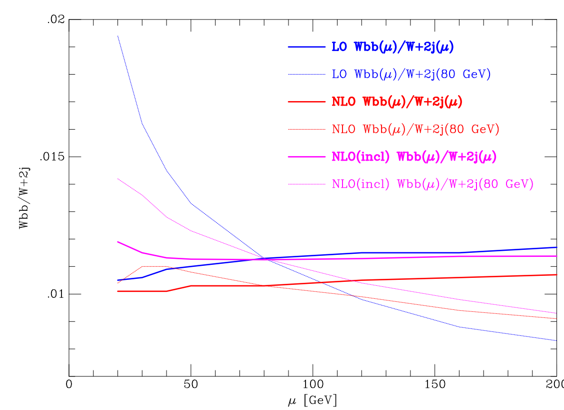
- VECBOS suffers from the same leading order uncertainty, albeit in a ratio now.
- We can calculate the $Wb\bar{b}$ cross-section at NLO in MCFM. This has a much reduced scale dependence, but suffers from no showering and massless b's.
- Another option is to calculate the same fraction that is calculated by LO+Herwig, but at NLO.
- One sees a much reduced scale dependence in each of the cross-sections at NLO, but . . .
  - If we choose the same scales in the numerator and denominator, is the ratio also stable?
  - If the same scale is not appropriate, is this ratio useful? $Wb\bar{b}$ is simply gluon-splitting at LO, suggesting a different renormalization scale may be appropriate.

Scale dependence - $Wb\bar{b}$ *vs.* $W+2$ *jets*



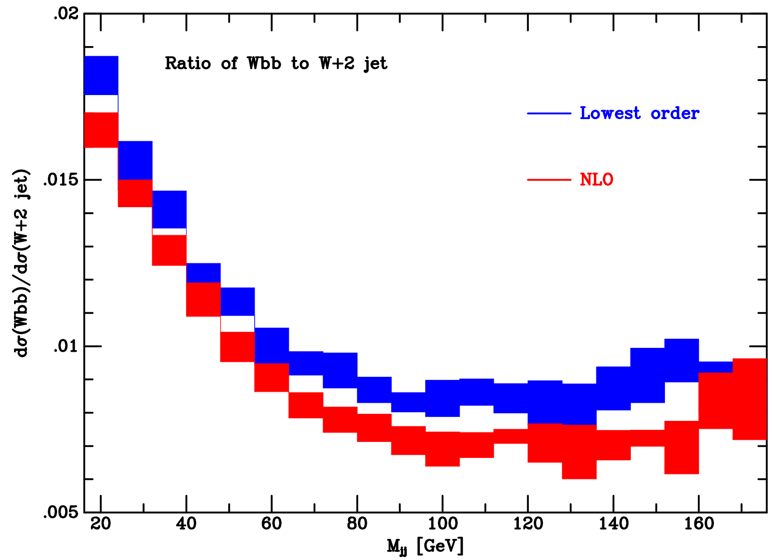


Ratio is much more stable at NLO, whether or not the same scale is used for $Wb\bar{b}$ as for $W+2$ jets.



Heavy flavour fraction vs. m_{JJ}

- Look at the variation of the ratio as the scale is changed (in both numerator and denominator) from ~ 30 GeV up to ~ 160 GeV.



- The ratio of b-tagged to untagged jets changes little at NLO and appears to be predicted reasonably well by perturbation theory.
- The fraction peaks at low M_{jj}, but in the reliable domain $M_{jj} > 60$ GeV, the value is fairly constant $\sim 0.8\%$.

Summary of MCFM

- MCFM is a state-of-the-art Monte Carlo for making NLO predictions at hadron colliders.
- The currect version of the program is MCFM v3.4, which can be found at `mcfm.fnal.gov`.
- This includes NLO corrections for $W/Z+2$ jets, which demonstrate the expected improvements such as a reduction in scale dependence. However, expectations for some observables are considerably changed at NLO.
- Implications of these calculations for the Tevatron are being studied. For instance, the fraction of a $W+2$ jet sample that contains two b-jets can be predicted at NLO and appears fairly robust
- There are many interesting studies to be done - from tests of QCD to backgrounds for new physics.

JC and Huston

Long-term outlook

- It seems clear that performing NLO calculations on a case-by-case basis is not the way of the future
- An automated approach, combining algebraic and numerical recipes, appears both promising (in terms of physics output) and feasible
  - Extensions of existing algorithmic tree-level programs (such as ALPGEN and Madgraph/MadEvent) seem inevitable
- However, even if such ambitious projects can be realized, the story does not end there
  - interpretation and grooming of results will still be very process-specific
  - jet-clustering, photon fragmentation, threshold effects, resummation and more will need to be considered